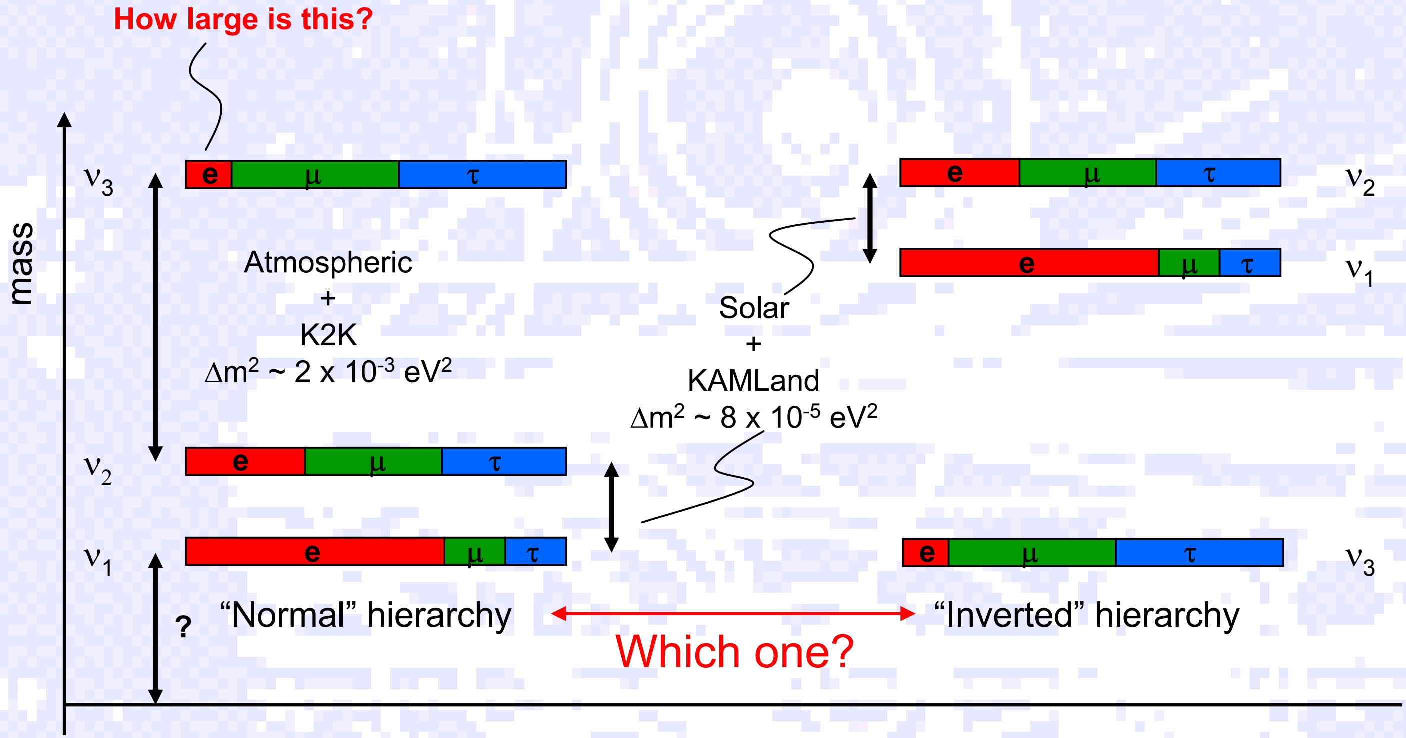
The NOνA Experiment

High Intensity Frontier Workshop
La Biodola
May 31, 2005

R. Ray
Fermilab

What we know, what we would like to know…



- Would like to have a more precise knowledge of mixing.
  - What is the ν_e component of ν_3? ($\theta_{13} \neq 0$)
  - Is ν_3 mostly ν_μ or ν_τ? ($\theta_{23} > \pi/4$, $\theta_{23} < \pi/4$, or $\theta_{23} = \pi/4$)
- Is $\Delta m^2_{23} > 0$ or < 0?
- Is CP violated? ($\delta \neq 0,\pi$)

Physics Motivations

θ_{13}

- Magnitude of θ_{13} determines the feasibility of experimentally addressing other questions.
- Many models that predict a full spectrum of possible values (see talk from A. De Gouvea earlier in the workshop)
- A measurement will eliminate most models

Mass Hierarchy

- Many models still in play consistent with normal, inverted or quasi degenerate hierarchy.
- Inverted hierarchy raises doubts about quark-lepton symmetry and rules out many GUT models.
- For normal hierarchy, generic seesaw models work fine, as do most GUT models that address quark and lepton masses and mixings.
- Long baseline experiments generally need to know the hierarchy to measure the CP phase.

Physics Motivations (Cont.)

CP Phase

- Symmetry with quark sector?
- Demonstration of leptonic CP violation enhances possibility that matter asymmetry could have been generated in the lepton sector.
- Unambiguous connection not required, though predicted in some models. Even with zero CP phase in light neutrinos still possible to generate sufficient baryon asymmetry via other leptogenesis mechanisms.

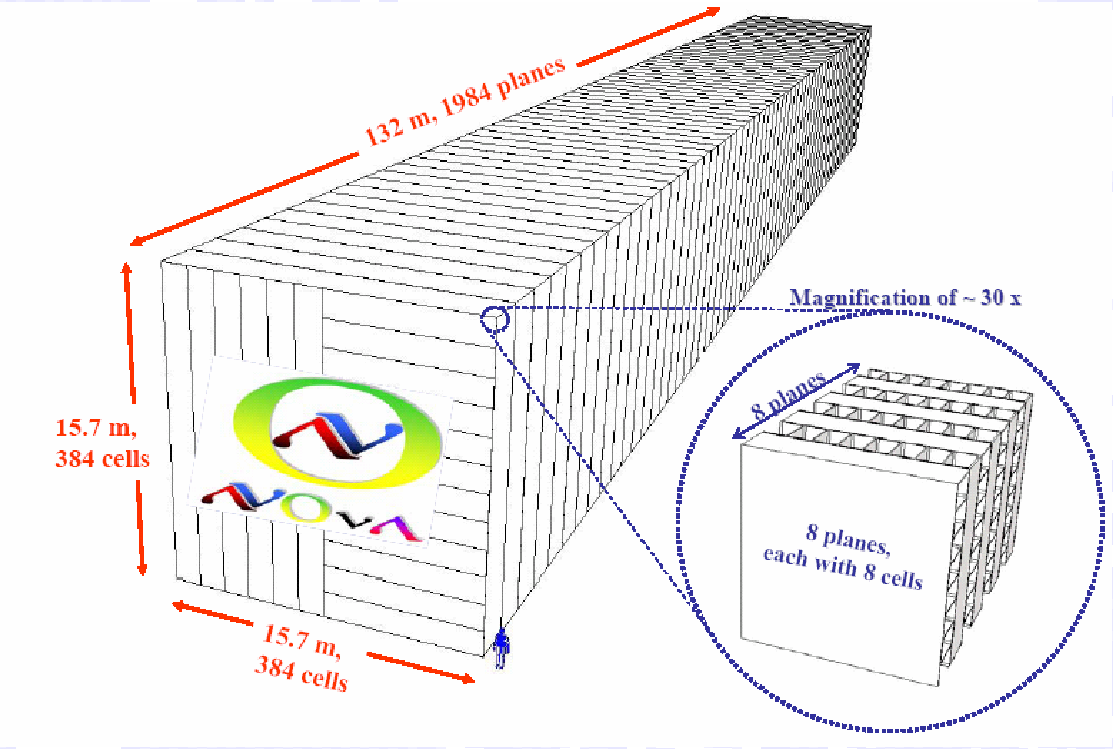
Is θ_{23} Maximal?

- Current measured value consistent with maximal, but with large error.
- If mixing is maximal, could be due to unknown symmetry.
- If mixing is maximal, description of lepton mixing severely constrained.
- If mixing is not maximal it complicates comparison of long baseline and reactor experiments

NOνA

NuMI Off-Axis ν_e Appearance Experiment

Argonne, Athens, Caltech, UCLA, Fermilab, College de France, Harvard, Indiana, ITEP, Lebedev, Michigan State, Minnesota/Duluth, Minnesota/Minneapolis, Munich, Stony Brook, Northern Illinois, Ohio, Ohio State, Oxford, Rio de Janeiro, Rutherford, South Carolina, Stanford, Texas A&M, Texas/Austin, Tufts, Virginia, Washington, William & Mary, Wisconsin



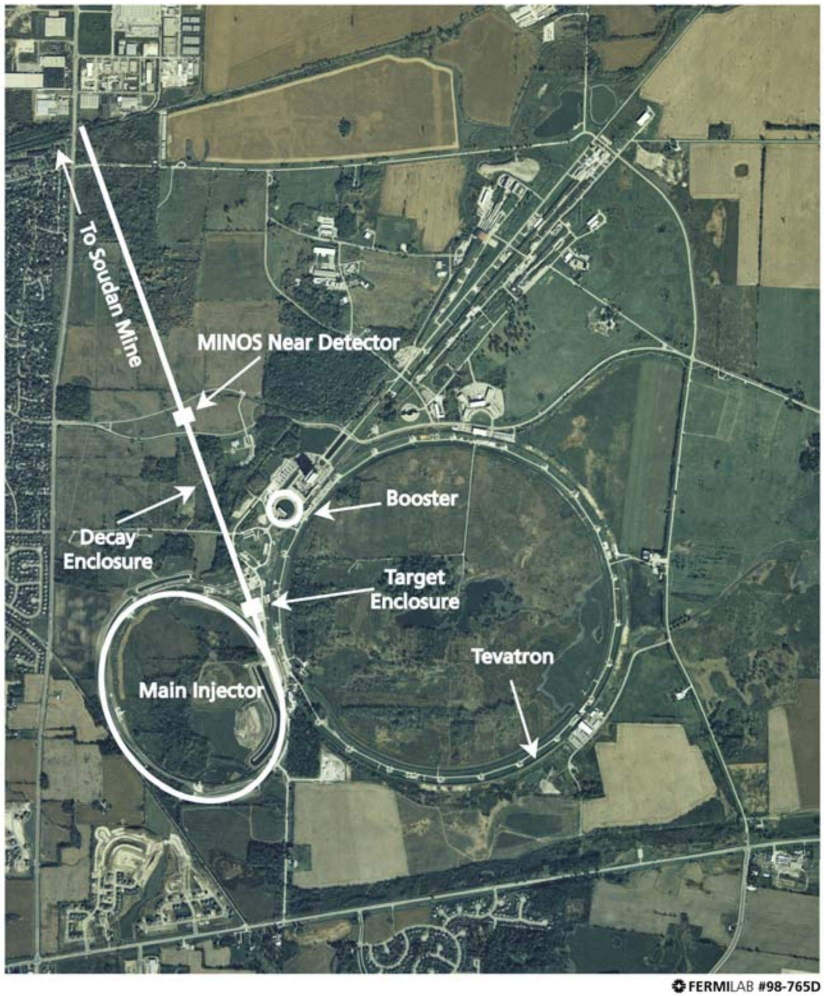
Goals of the NOνA Experiment

- Observe ν_e appearance
- Sensitivity to $Sin^2(2\theta_{13})$ a factor of 10 below CHOOZ sensitivity, i.e. down to ~ 0.01
- $Sin^2(2\theta_{23})$ measurement to 2% accuracy
- Resolve or contribute to determination of mass hierarchy via matter effects
- Begin to study CP violation in lepton sector
- Investigating possibility of supernova detection.

How NOνA Will Meet its Goals

- Reduce backgrounds to ν_e appearance search by going off the NUMI beam axis for a narrow-band beam. Will use NUMI Medium Energy configuration.
- Increase flux/POT at oscillation max by ~ x2 by going off-axis
- Increase detector mass a factor of 6 over MINOS while reducing cost/kiloton by a factor of 3
- 80% active detector design (compared to 1.5 X_0 sampling in MINOS)
  - electron showers appear as "fuzzy" tracks with 1-4 hits/plane/view
  - allow better separation of γ's from π^0 decays
  - good energy resolution to focus on signal energy region
- Choose long baseline to enhance matter effects

NOνA Uses the Existing NuMI Beam

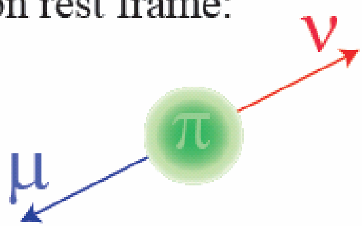


- 120 GeV protons extracted from the Main Injector in a single turn (8.7μs)
- 1.9 s cycle time *i.e.* ν beam `on' for 8.7 ms every 1.9 s
- 2.5×10^{13} protons/pulse initially
- 2.5×10^{20} protons/year initial intensity
- 0.25 MW on target !

Off-Axis Neutrino Beams

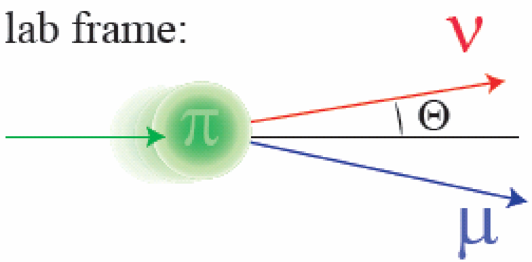
First proposed by BNL E-889

In pion rest frame:

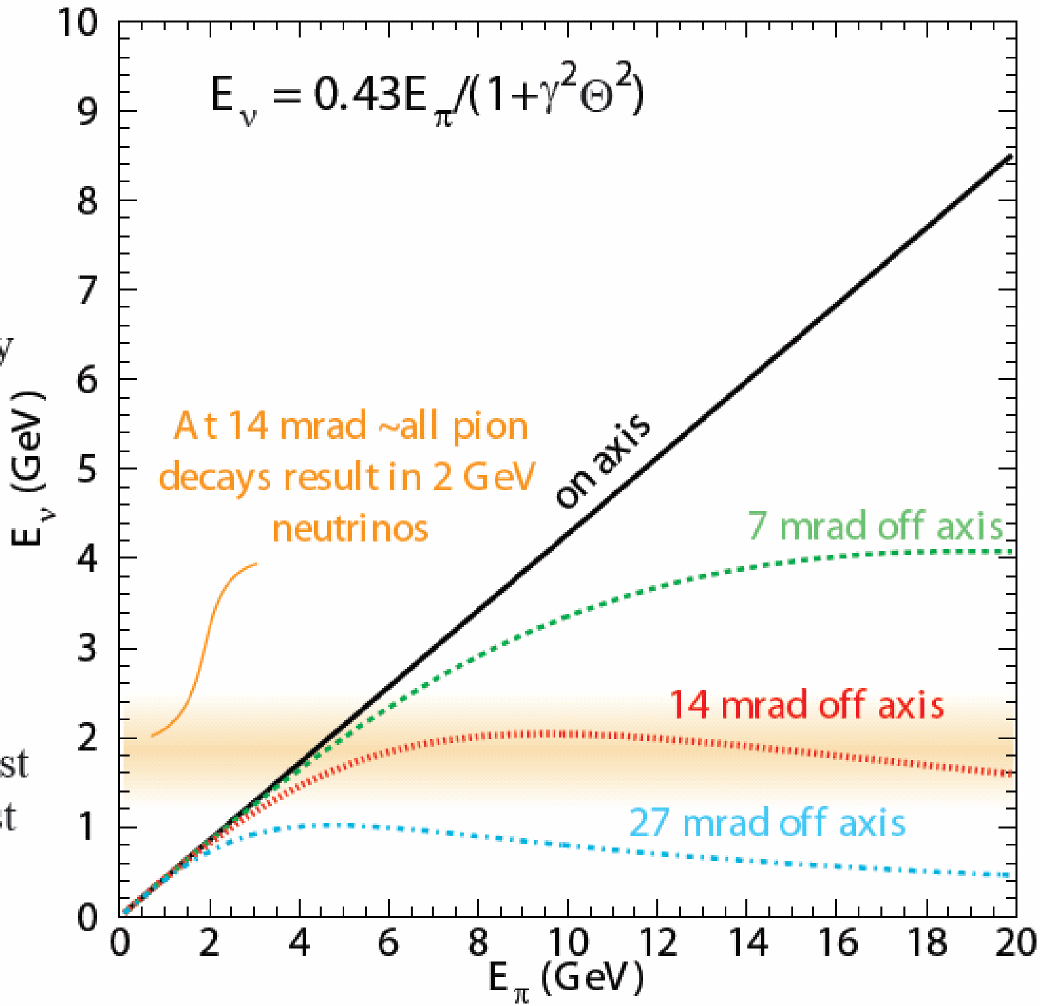


Neutrino and muon energy completely determined by energy conservation

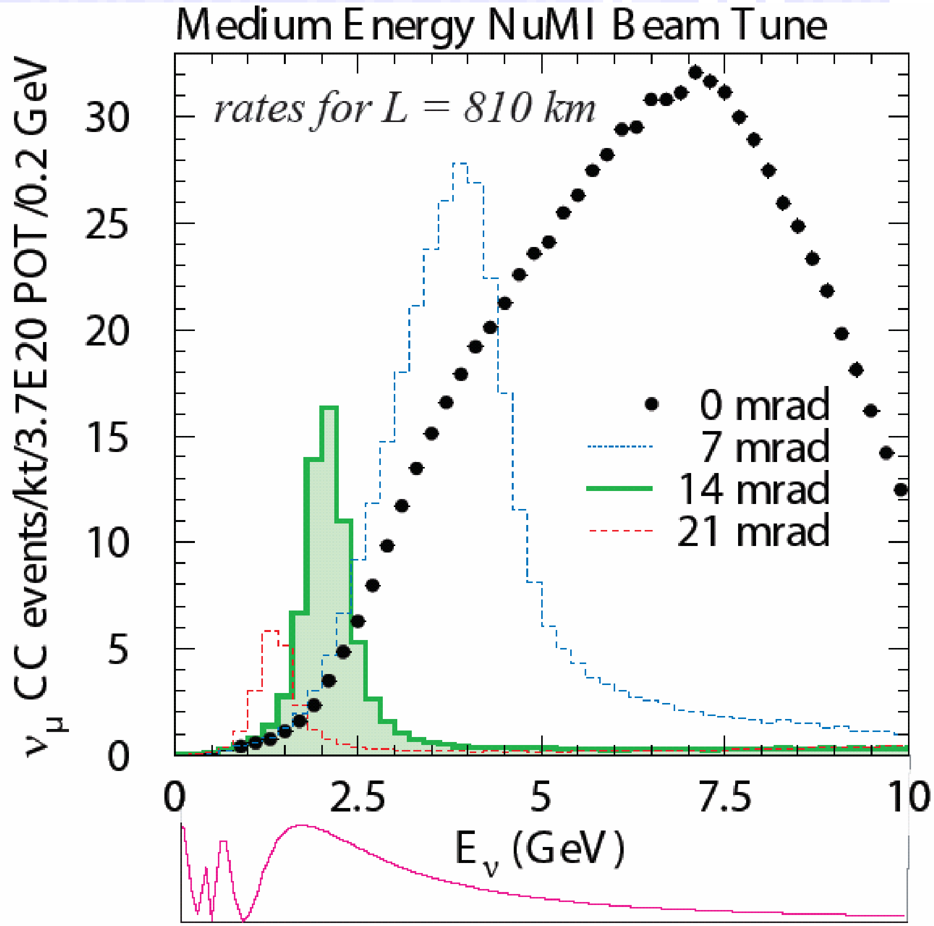
In lab frame:



Neutrino energy depends on boost and angle between neutrino boost direction



NUMI Offaxis Neutrino Spectra



- 14 mrad off-axis beam peaks just above oscillation max at ~ 2 GeV with ~20% width
- High energy tail suppressed
  - Reduces NC and τ backgrounds
- Main peak from π decays. K decay ν at much wider angles.
  - Spectrum prediction insensitive to knowledge of k/π ratio

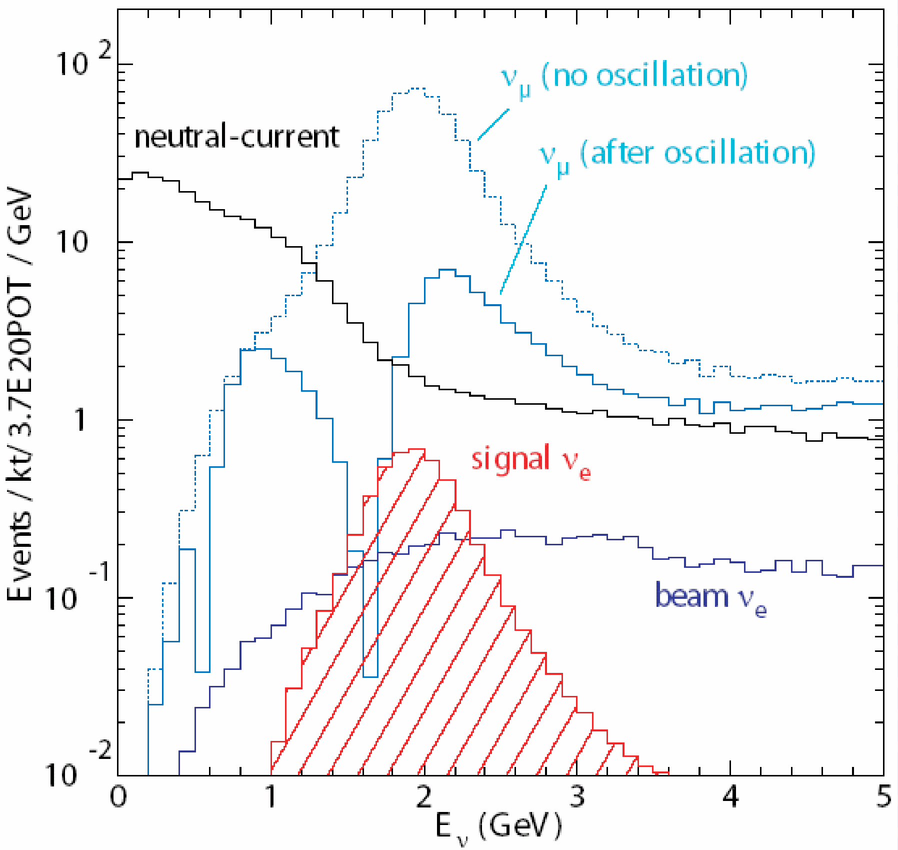
Event Rates

Event rates calculated for

- L=810 km, 12 km off-axis
- $\Delta m^2_{23} = 2.5 \times 10^{-3}\ eV^2$
- $\sin^2 2\theta_{23} = 1$
- $\sin^2 2\theta_{13} = 0.01$

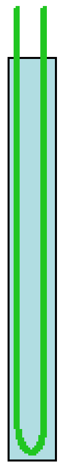
To Reject Background:

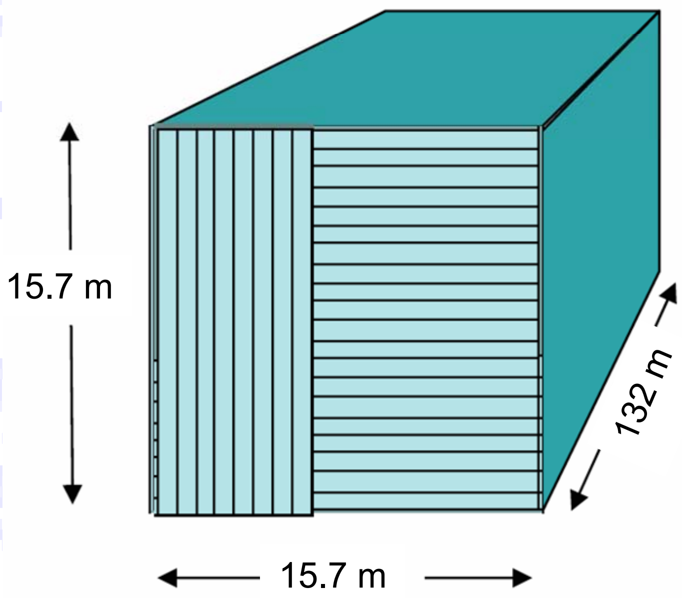
- 50:1 rejection of ν_μ CC required
  ⇨ Easy!
- Need 100:1 NC rejection
  ⇨ fine grained, low density
- Good energy resolution
  ⇨ reject beam ν_e



The NOνA Far Detector

- 30 kT, low Z tracking calorimeter
- 80% active material (by weight).
- Optimized for detecting 2 GeV electrons.
- PVC extrusions filled with Liq. Scint.
- Add TiO_2 to PVC to maximize reflectivity.
  - Cell size of 3.87cm x 6.0 cm x 15.7 m
  - 12 extrusions/plane
  - 32 cells/extrusion
  - 1984 planes
  - = 23,808 extrusions
  - = 761,856 channels
- 0.8 mm looped WLS fiber into APD readout





APD Readout

- Cooled to -15° C
- Q.E. 85%
- 25 p.e. at far end
- 250 e noise
- S/N 10:1

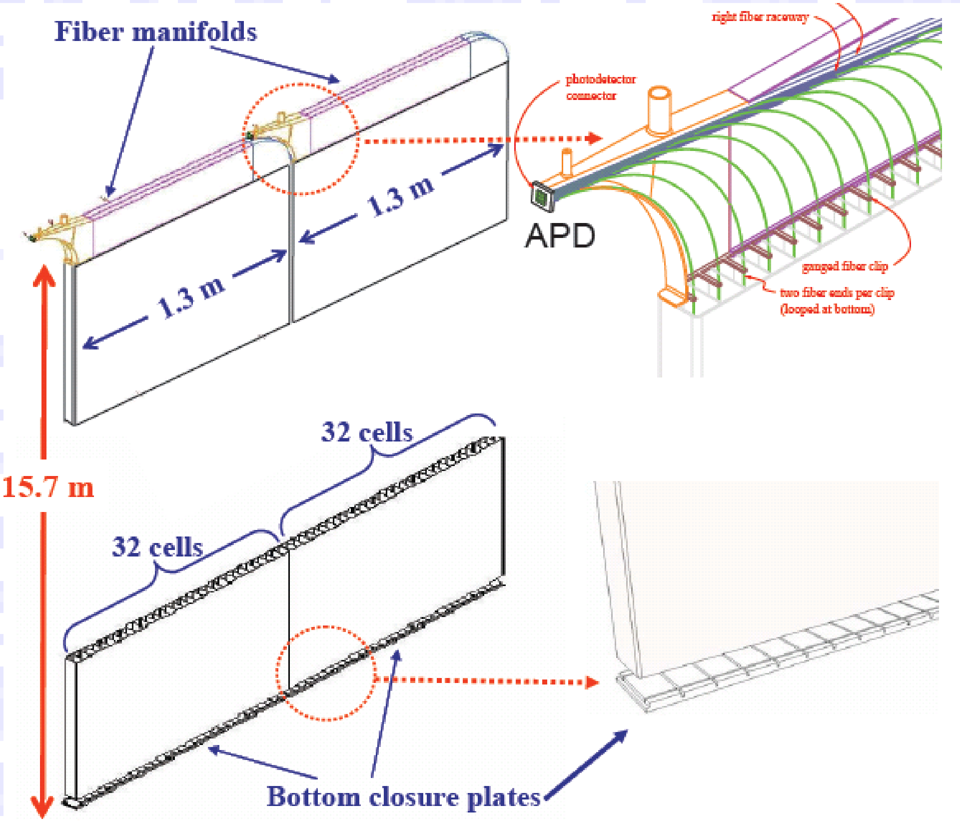
NOνA Structure

The basic component is a 32 cell rigid PVC extrusion

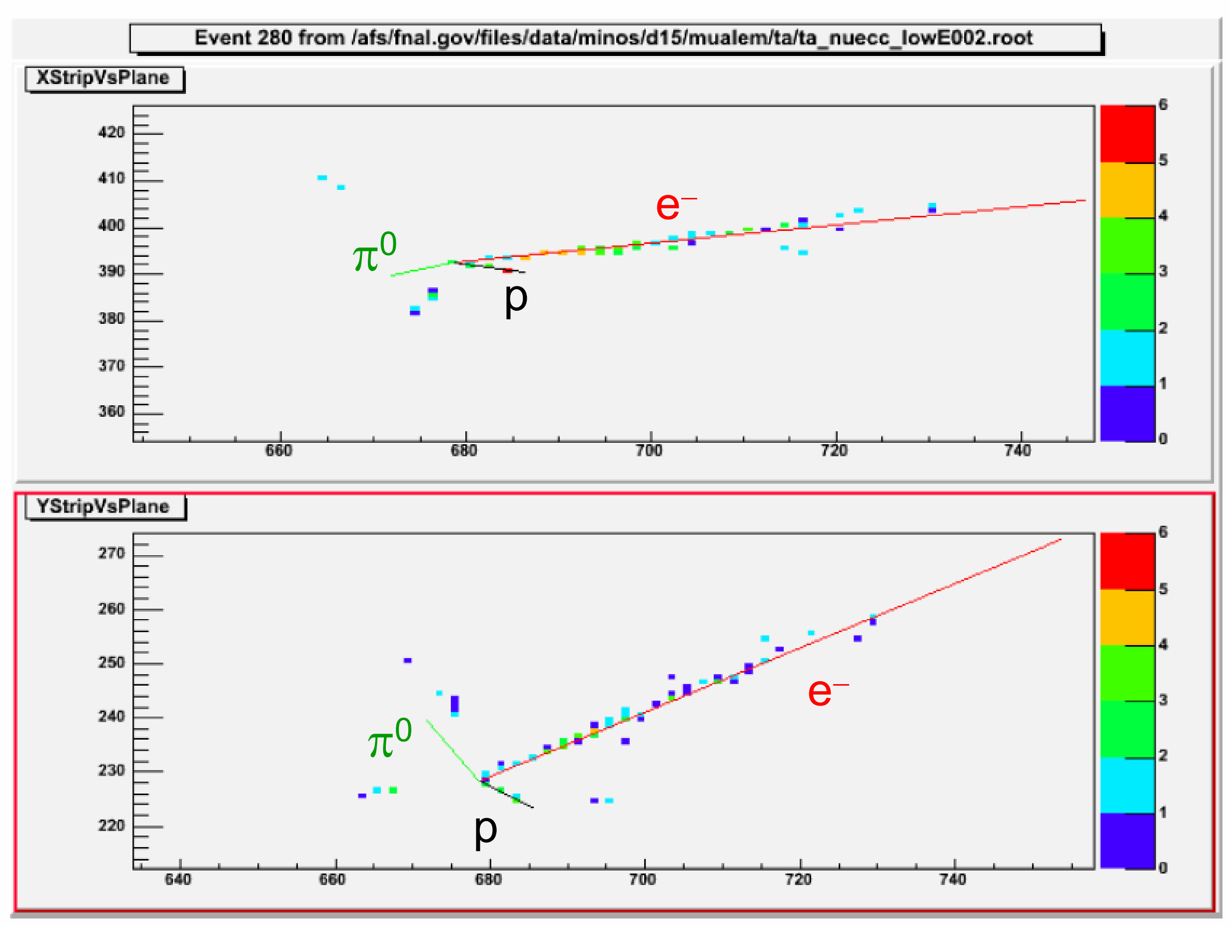
Outer cell walls are 3 mm thick, inner webs 2 mm thick.

~24,000 such modules

Basic designs for bottom closure plates and top fiber manifolds exist.



Typical NOνA Event: $\nu_e A \rightarrow p\, e^- \pi^0$, E_ν = 1.65 GeV



Signal efficiency 24%

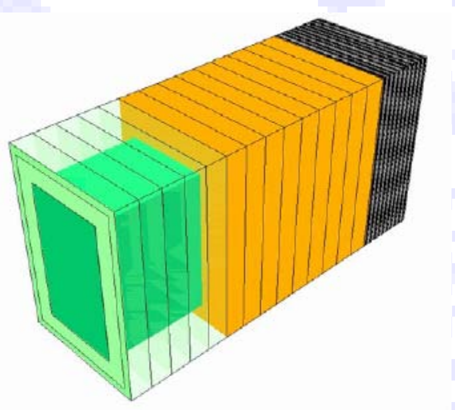
signal/background 7.3

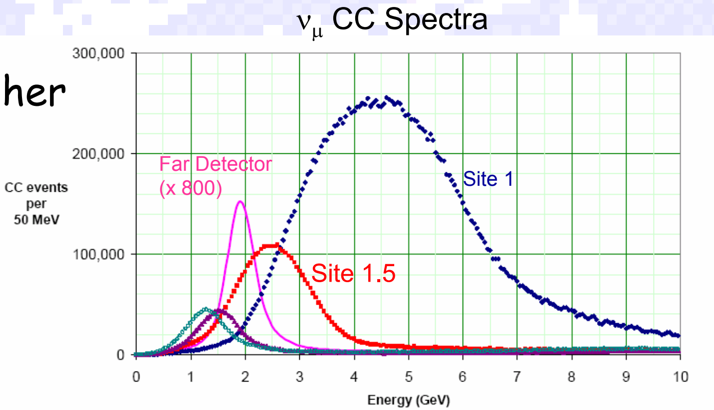
signal/sqrt(bg.) 32

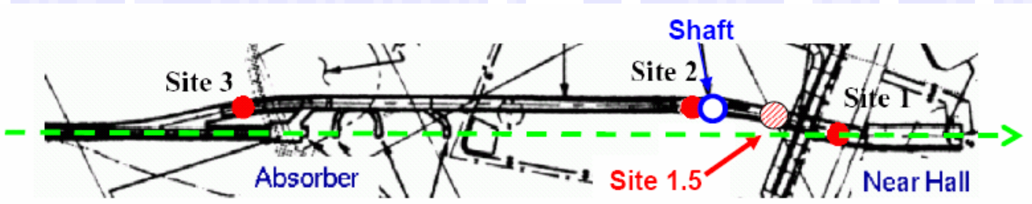
The large information content in these events gives us confidence we can improve our simulated signal efficiency beyond 24% with no background increase.

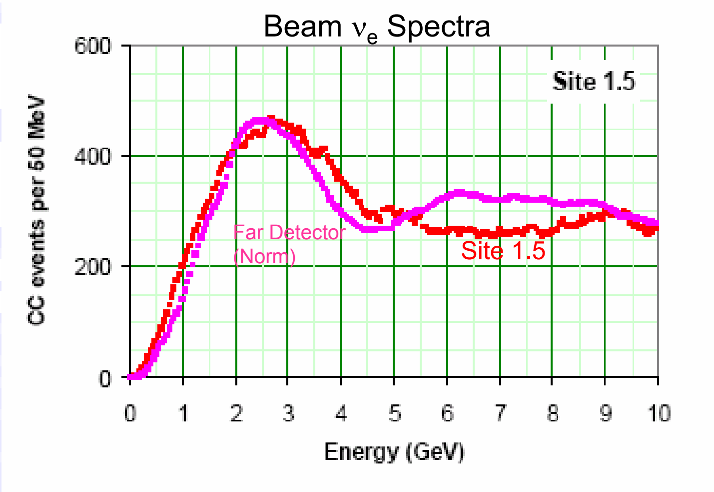
NOνA Near Detector

- ~ 1 km from NUMI target
- Fits in several existing locations in NUMI access tunnel
  - 3.5 m x 4.8 m x 9.6 m
  - Includes veto, shower containment, muon catcher
- No single location optimizes all parameters
  - Make movable or build more than 1









Fermilab Proton Plan

	Booster Batch Size	Main Injector Load	Cycle Time	MI Intensity	Booster Rate*	Total Proton Rate	Annual Rate at end of Phase	
		(AP + NuMI)	(sec)	(protons)	(Hz)	(p/hr)	NuMI	BNB
Actual Operation								
July, 04	5.0E+12	1+0	2.0	0.5E+13	5.1	0.8E+17	0	3.3E+20
Proton Plan								
Phase I	5.10E+12	2+1→2+5	2.0	3.6E+13	6.3	1.0E+17	2.0E+20	1.5E+20
Phase II	5.3E+12	2+5	2.0	3.7E+13	7.5	1.2E+17	2.2E+20	2.8E+20
Phase III	5.50E+12	2+9	2.2	6.0E+13	8.3	1.5E+17	3.4E+20	2.2E+20
Beyond Scope of Present Plan								
11 Hz	5.50E+12	2+9	2.2	6.1E+13	11.0	2.0E+17	3.4E+20	5.0E+20

2008

TABLE 6: Performance parameters at the completion of each phase of operation.
* Booster rate is limited by radiation levels, except for the 11 Hz case

http://www.fnal.gov/directorate/program_planning/Nov2004PACPublic/Draft_Proton_Plan_v2.pdf

Fermilab Proton Plan after 2009

Collider operations end in 2009

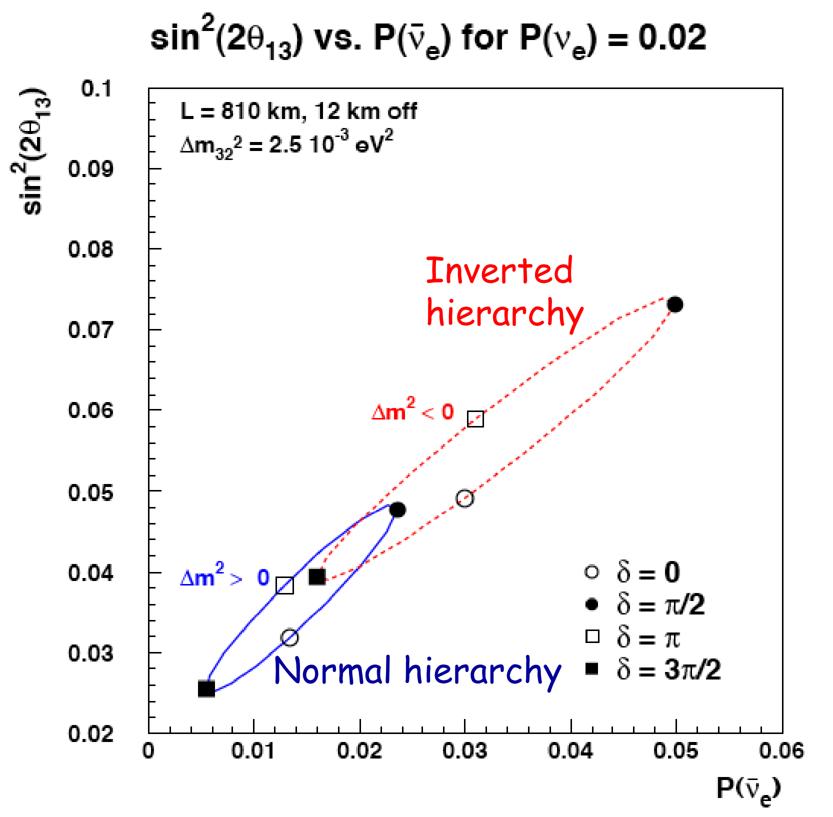
- Proton bunches in MI used to $\bar{p}$ now available to NuMI → × 11/9
- No NuMI downtime due to shot setup (10%) or antiproton transfers to Recycler (5%) → × 1.176
- Load 11 booster batches into Recycler and transfer from Recycler to MI in a single booster cycle. MI cycle time reduced from 2.2 s to 1.467 s → × 1.5
- $(1.22)(1.176)(1.5)(3.4 \times 10^{20}$ p/yr$) = 7.3 \times 10^{20}$ p/yr

Assume 90% → 6.5×10^{20} p/yr
0.65 MW Beam!

- A Fermilab Proton Driver would provide 25×10^{20} pot/yr, a factor of × 4.

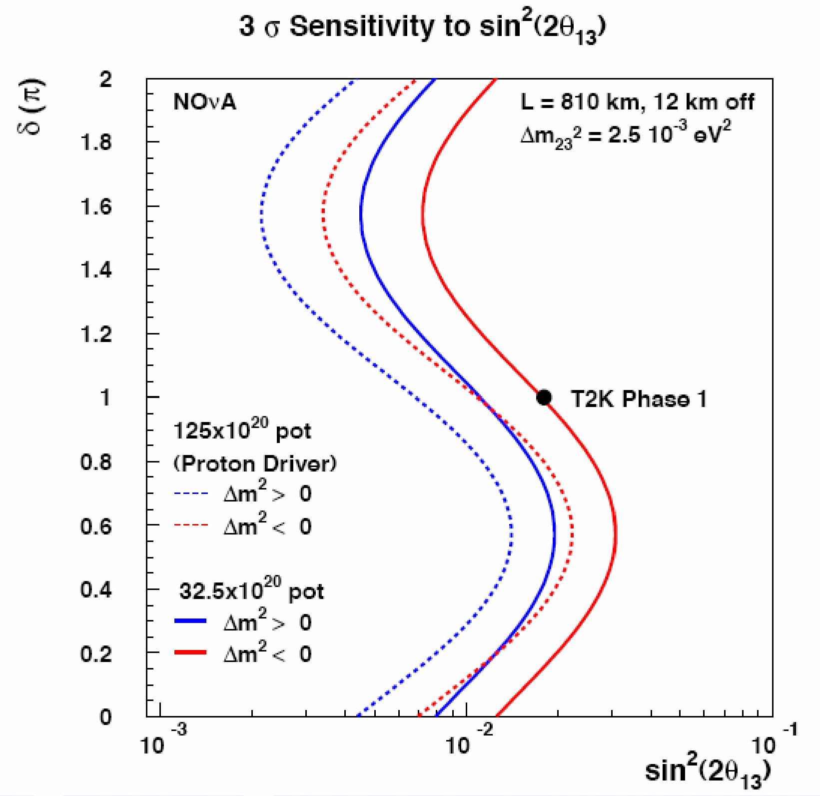
Interpreting what we measure

- Experiments measure oscillation probabilities
- Ambiguities in $\sin^2(2\theta_{13})$ due to CP phase δ and mass hierarchy
- Comparison of NOνA and T2K at different baselines can break ambiguities
- Possibly use a 2d NUMI off-axis detector at the 2d oscillation maximum
- Sensitivity varies with CP phase



$\mathrm{Sin}^2(2\theta_{13})$ Sensitivity With and Without a Proton Driver

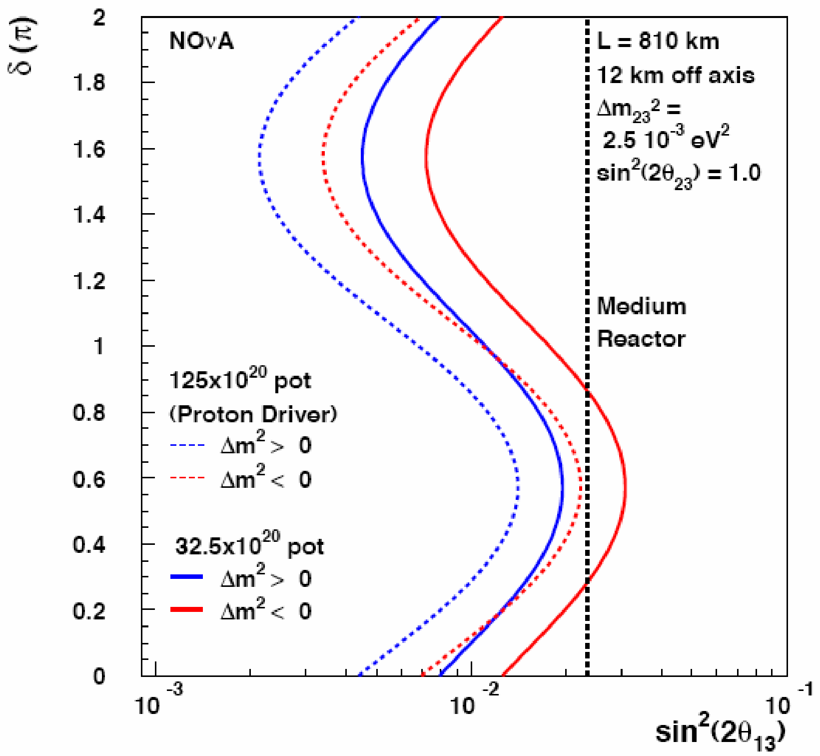
- Vertical axis is δ in units of π for which a 3σ measurement could be made.
- 5% systematic error on background determination included.



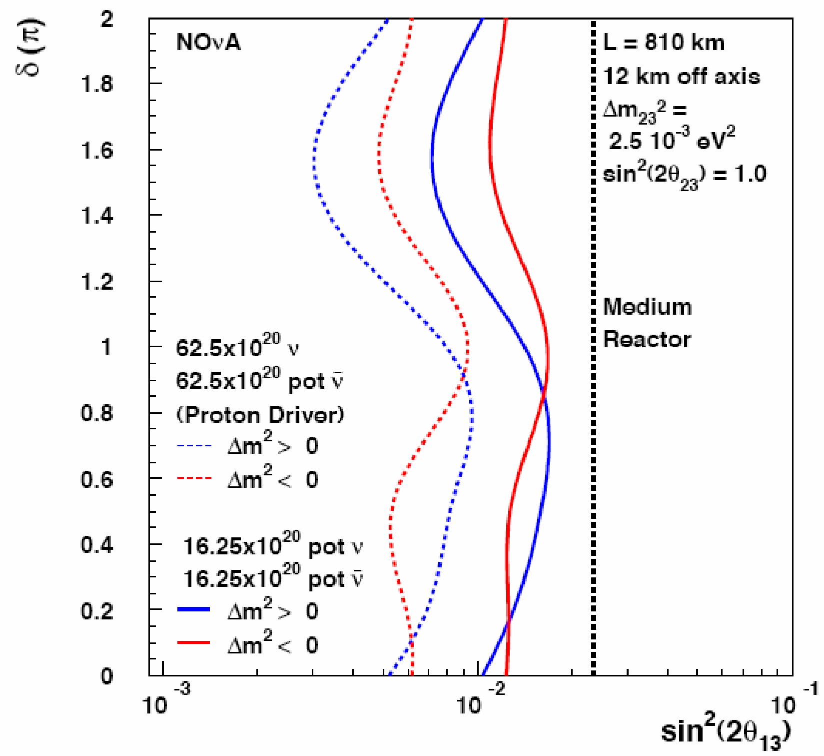
NOνA 3σ Sensitivity to $\sin^2(2\theta_{13})$ Compared to Medium Reactor Experiment

Medium Reactor" is a Braidwood or Daya Bay class experiment
(1% sensitivity at 1.28 σ ("90% CL")

5 years of neutrino running



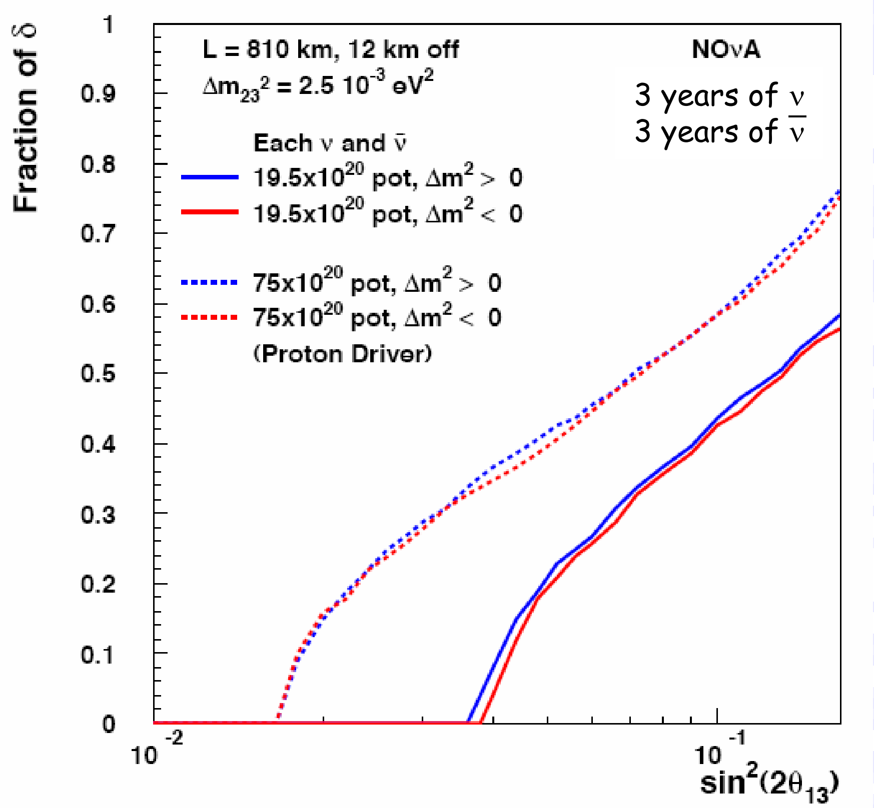
2.5 years each of ν and $\bar{\nu}$



Resolving the Mass Hierarchy

Fraction of possible δ values for which there is a 95% C.L. resolution of the mass hierarchy

95% C.L. Resolution of Mass Hierarchy



There is a reasonable region of parameter space for which NOνA can resolve hierarchy. Proton Driver extends reach by factor of 2.

Resolving the Mass Hierarchy (cont.)

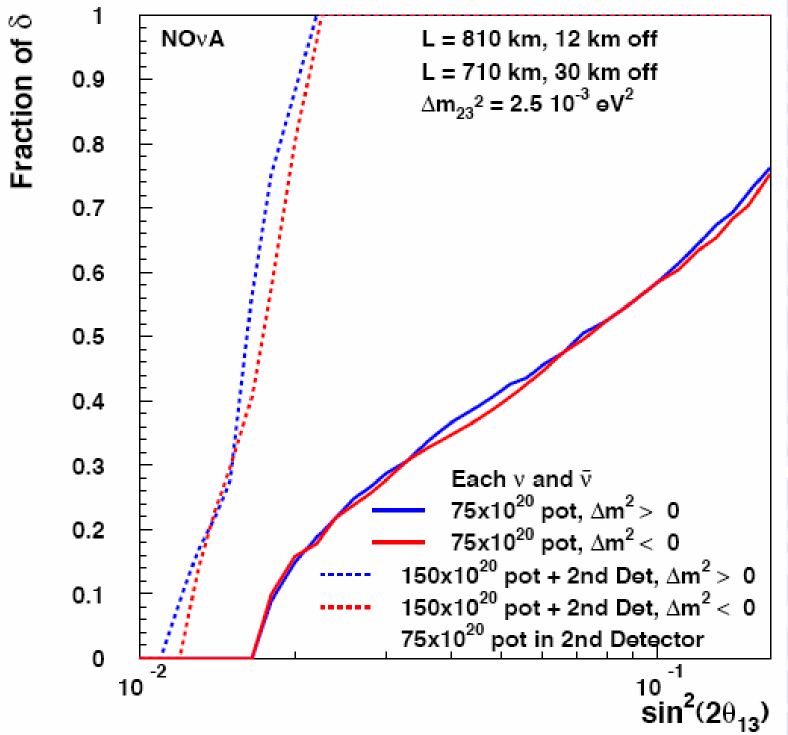
NOνA alone and with an additional off-axis detector at the 2d maximum

At 2d oscillation maximum

- L=710 km, 30 km off-axis
- Energy lower by x 3
  - ⇒ Matter effect smaller by x 3
  - ⇒ CP violation larger by x 3
- Liquid Argon TPC? Water Cerenkov?

Mass hierarchy resolved for all δ for $Sin^2(2\theta_{13})$ > ~ 0.015

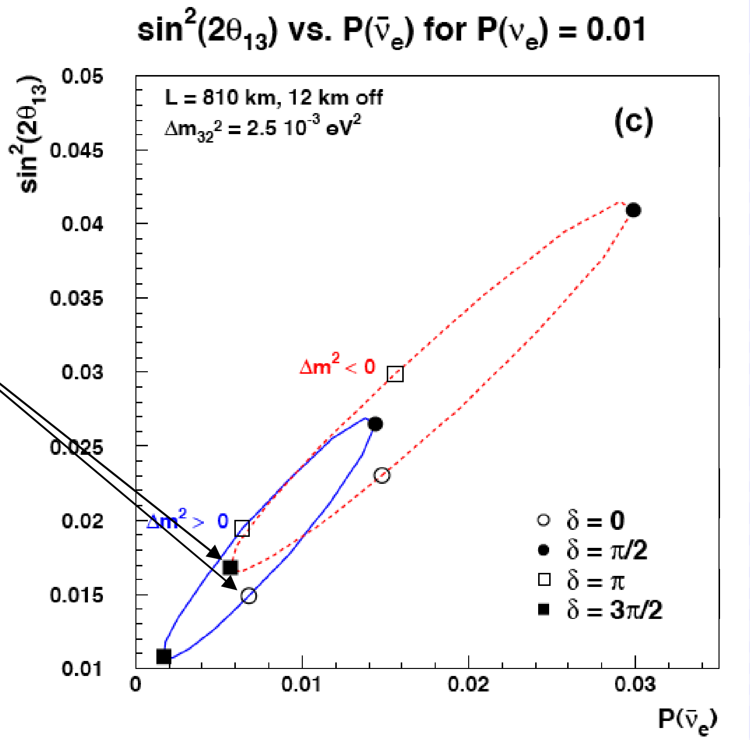
95% C.L. Resolution of Mass Hierarchy



2 years into the PD run, realize the need for the 2nd off-axis detector. Build in 4 years, run for 6 years. Thus, 12 years running of NOνA with PD and 6 years of running the second detector.

Sensitivity to CP Violation

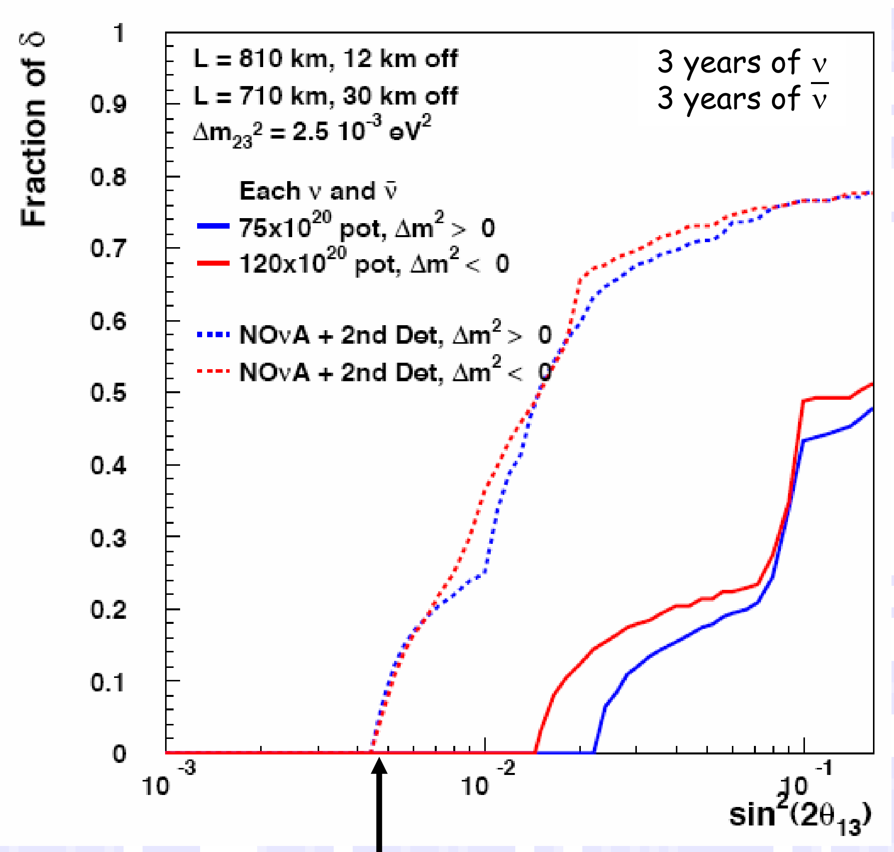
- Long baseline experiments generally need to know the hierarchy to measure the CP phase
- Maximal CPV for one mass ordering can have ν and $\bar{\nu}$ probabilities corresponding to no CPV for the other mass ordering



- Neither NOνA nor T2K can demonstrate CP violation in 6 years of running without enhanced proton sources

Sensitivity to CP Violation (cont.)

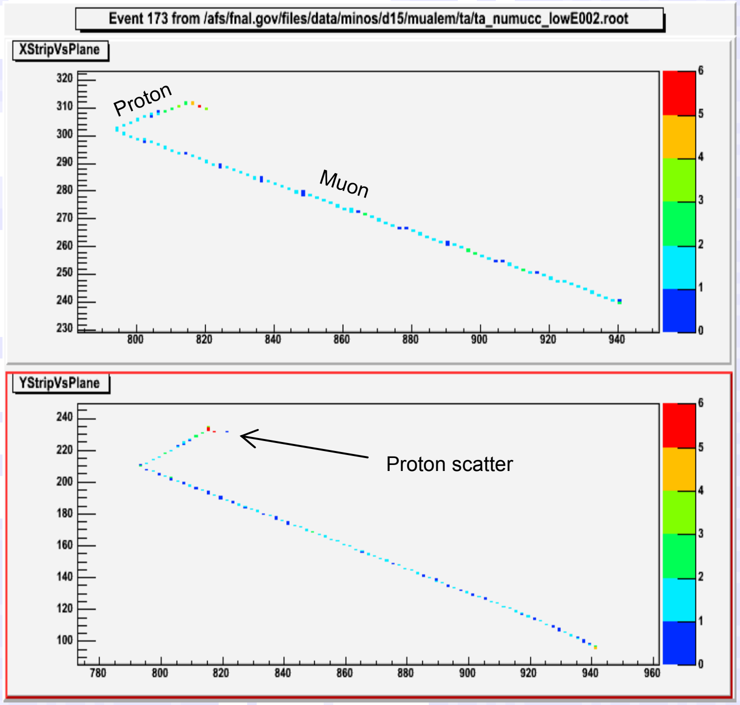
Fraction of possible δ values for which there is a 3σ demonstration of CPV i.e. δ is neither 0 nor π for both mass orderings.



NOνA with 2nd NuMI off-axis detector

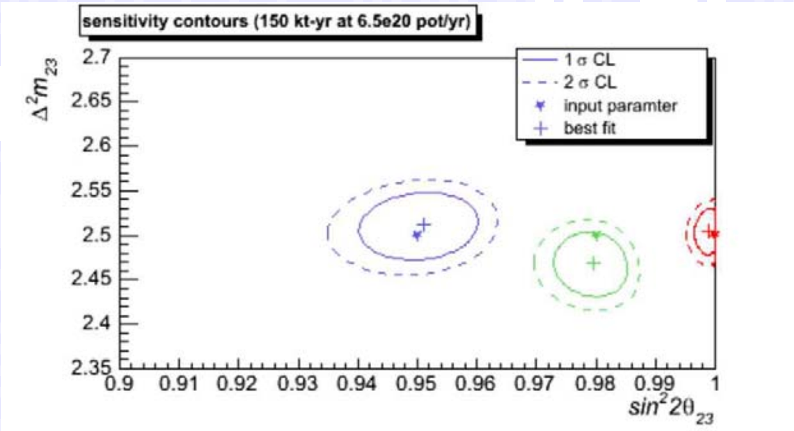
Precise Determination of $\sin^2(2\theta_{23})$

- Important because:
  - If mixing is maximal, could be due to unknown symmetry
  - $\nu_\mu \rightarrow \nu_e$ oscillation is proportional to $\sin^2(\theta_{23})\sin^2(2\theta_{13})$
  - If mixing is not maximal, this leads to an ambiguity in comparing reactor and accelerator results.
  - A comparison of $\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ is a sensitive test of CPT since matter effects are suppressed in this channel.



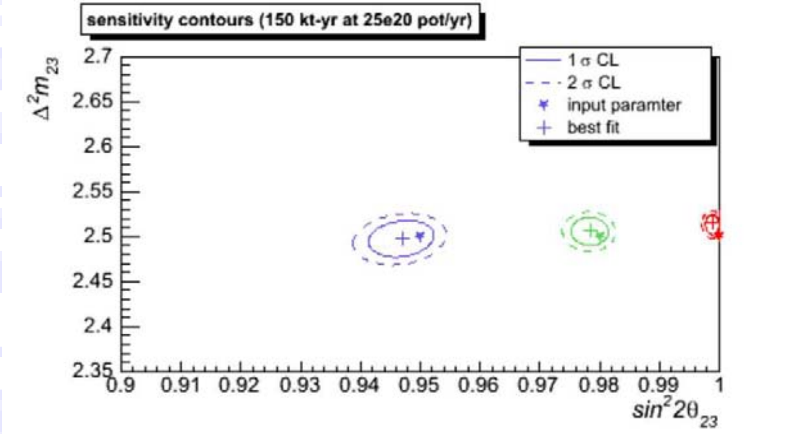
- Precision measurement requires
  - good statistics
  - good ν energy resolution
  - good control of systematics
- Use totally contained quasi-elastic events
  - Very clean, essentially no NC background
  - Can measure $\sin^2(2\theta_{23})$ to ~ 1-2% level

Precise Determination of $\sin^2(2\theta_{23})$



1σ and 2σ contours for simultaneous measurement of Δm^2_{32} and $\sin^2(2\theta_{23})$ for a 5 year ν run without a Proton Driver.

5 year ν run with Proton Driver



For maximal mixing, error on $\sin^2(2\theta_{23})$ is about 0.004 without Proton Driver and 0.002 with a Proton Driver.

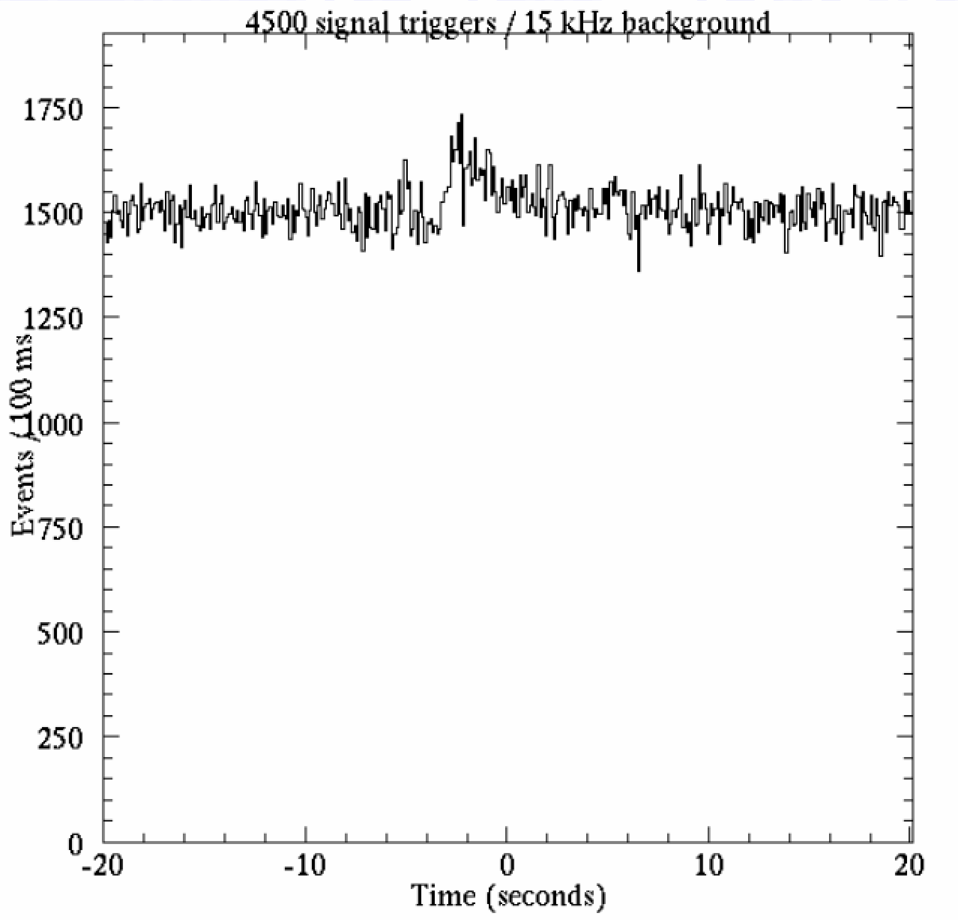
Summary

- NOνA provides a flexible approach to studying all of the parameters of neutrino oscillations.
- NOνA can do physics now. The NOνA detector is simple and straightforward and can be built today.
- A Proton Driver is necessary to measure the CP phase and possibly the mass hierarchy.
- Final Comments
  - NOνA was approved by Fermilab PAC in April, 2005
  - NuSAG review by funding agencies to report this Fall.
  - NOνA and Fermilab are very open to new collaborators

NOνA Milestones

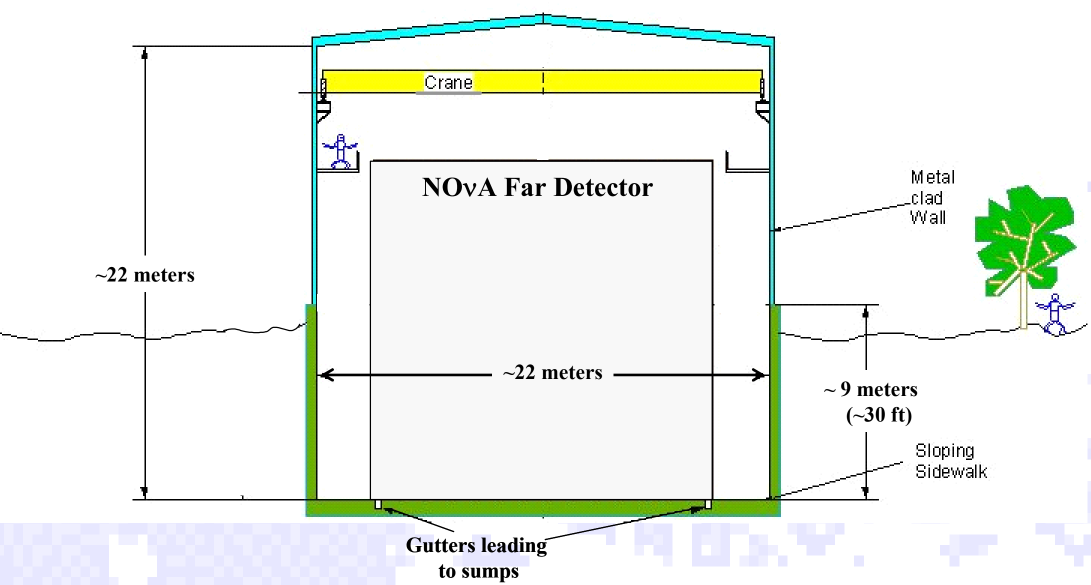
Milestone	Date (in months relative to Project Start)	Proposed Calendar Date	FY
Project Start	t_0	October, 2006	07
Order extrusions and fiber	t_0+1	Nov., 2007	07
Start extrusion module factories	t_0+12	October, 2007	08
Start operation of Near Detector	t_0+21	July, 2008	08
Far building complete	t_0+31	May, 2009	09
Start Construction of Far detector	t_0+31	May, 2009	09
First kiloton operational	t_0+36	Oct., 2009	10
First 15 kilotons operational	t_0+47	June 2010	10
Full 30 kilotons operational	t_0+57	July, 2011	11

Sensitivity to a Galactic Supernova



1800 events in the 1st second for a supernova 10 kps away

Far Site Building



- Secondary containment with building below grade
  - ✓ Epoxy paint coated bathtub (green) holds full inventory of scintillator
- Access
  - ✓ Catwalks for the top
  - ✓ Side aisles for scissor lifts
- "Lean-to" attachment (not shown) for liquid scintillator tanker storage
- HVAC 20 ± 10 °C
  - ✓ Scintillator damage below -20 °F, > +110 °F
- Truck staging area at grade level